32. High-Energy Collider Parameters

High-Energy Collider Parameters: e^+e^- Colliders (I)

Table 32.1: Updated in March 2020 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting. Parameters for the defunct SPEAR, DORIS, PETRA, PEP, TRISTAN, and VEPP-2M colliders may be found in our 1996 edition (Phys. Rev. **D54**, 1 July 1996, Part I).

	VEPP-2000 (Novosibirsk)	VEPP-4M (Novosibirsk)	BEPC (China)	BEPC-II (China)	DAΦNE (Frascati)
Physics start date	2010	1994	1989	2008	1999
Physics end date	—	—	2005	—	—
Maximum beam energy (GeV)	1.0	6	2.5	1.89 (2.35 max)	0.510
Delivered integrated luminosity per exp. (fb^{-1})	0.25	0.05	0.11	24.6	$\approx$ 4.7 in 2001-2007 $\approx$ 2.7 w/crab-waist $\approx$ 1.8 since Nov 2014
Luminosity (10^{30} $cm^{-2}s^{-1}$)	50	20	12.6 at 1.843 GeV 5 at 1.55 GeV	1000	453
Time between collisions (μs)	0.04	0.6	0.8	0.008	0.0027
Full crossing angle (μ rad)	0	0	0	2.2×10^4	5×10^4
Energy spread (units 10^{-3})	0.71	1	0.58 at 2.2 GeV	0.52	0.40
Bunch length (cm)	4	5	$\approx$ 5	$\approx$ 1.2	low current: 1 at 15mA: 2
Beam radius (10^{-6} m)	125 (round)	H:1000 V:30	H:890 V:37	H:347 V:4.5	H:260 V:4.8
Free space at interaction point (m)	$\pm$0.5	$\pm$2	$\pm$2.15	$\pm$0.63	$\pm$0.295
Luminosity lifetime (hr)	continuous	2	7–12	1.5	0.2
Turn-around time (min)	continuous	18	32	4 (topping up)	2 (topping up)
Injection energy (GeV)	0.2–1.0	1.8	1.55	1.89	on energy
Transverse emittance (10^{-9} m)	H:150 V:150	H:200 V:20	H:660 V:28	H:121 V:1.56	H:260 V:2.6
β^*, amplitude function at interaction point (m)	H:0.05 - 0.11 V:0.05 - 0.11	H:0.75 V:0.05	H:1.2 V:0.05	H:1.0 V:0.0129	H:0.26 V:0.009
Beam-beam tune shift per crossing (units 10^{-4})	H:850 V:850	500	350	383	440 (crab-waist test)
RF frequency (MHz)	172	180	199.53	499.8	356
Particles per bunch (units 10^{10})	8	15	20 at 2 GeV 11 at 1.55 GeV	3.8	e^-: 3.2 e^+: 2.1
Bunches per ring per species	1	2	1	119	100 to 105 (120 buckets)
Average beam current per species (mA)	160	80	40 at 2 GeV 22 at 1.55 GeV	851	e^-: 1250 e^+: 800
Circumference or length (km)	0.024	0.366	0.2404	0.23753	0.098
Interaction regions	2	1	2	1	1
Magnetic length of dipole (m)	1.1	2	1.6	outer ring: 1.6 inner ring: 1.41	outer ring: 1.2 inner ring: 1
Length of standard cell (m)	12	7.2	6.6	outer ring: 6.6 inner ring: 6.2	n/a
Phase advance per cell (deg)	H:745 V:385	65	$\approx$ 60	60–90 non-standard cells	—
Dipoles in ring	8	78	40 + 4 weak	84 + 8 weak	8
Quadrupoles in ring	24 + 4 s.c.	150	68	134+2 s.c.	48
Peak magnetic field (T)	2.4	0.6	0.903 at 2.8 GeV	outer ring: 0.677 inner ring: 0.766	1.2

High-Energy Collider Parameters: e^+e^- Colliders (II)

Table 32.2: Updated in March 2020 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting. ILC and CLIC parameters are documented in the Accelerator physics of colliders review.

	CESR (Cornell)	CESR-C (Cornell)	LEP (CERN)	SLC (SLAC)
Physics start date	1979	2002	1989	1989
Physics end date	2002	2008	2000	1998
Maximum beam energy (GeV)	6	6	100 - 104.6	50
Delivered integrated luminosity per experiment (fb^{-1})	41.5	2.0	0.221 at Z peak 0.501 at $65-100$ GeV 0.275 at >100 GeV	0.022
Luminosity (10^{30} $cm^{-2}s^{-1}$)	1280 at 5.3 GeV	76 at 2.08 GeV	24 at Z peak 100 at >90 GeV	2.5
Time between collisions (μs)	0.014 to 0.22	0.014 to 0.22	22	8300
Full crossing angle (μ rad)	$\pm$2000	$\pm$3300	0	0
Energy spread (units 10^{-3})	0.6 at 5.3 GeV	0.82 at 2.08 GeV	0.7→1.5	1.2
Bunch length (cm)	1.8	1.2	1.0	0.1
Beam radius (μm)	H:460 V:4	H:340 V:6.5	H:200→300 V:2.5→8	H:1.5 V:0.5
Free space at interaction point (m)	$\pm$2.2 ($\pm$0.6 to REC quads)	$\pm$2.2 ($\pm$0.3 to PM quads)	$\pm$3.5	$\pm$2.8
Luminosity lifetime (hr)	2–3	2–3	20 at Z peak 10 at >90 GeV	—
Turn-around time (min)	5 (topping up)	1.5 (topping up)	50	120 Hz (pulsed)
Injection energy (GeV)	1.8–6	1.5–6	22	45.64
Transverse emittance (10^{-9} m)	210 1	120 3.5	H:20–45 V:0.25→1	H:0.5 V:0.05
β^*, amplitude function at interaction point (m)	1.0 0.018	0.94 0.012	1.5 0.05	0.0025 0.0015
Beam-beam tune shift per crossing (10^{-4}) or disruption	250 620	e^-: 420 (H), 280 (V) e^+: 410 (H), 270 (V)	830	0.75 (H) 2.0 (V)
RF frequency (MHz)	500	500	352.2	2856
Particles per bunch (units 10^{10})	1.15	4.7	45 in collision 60 in single beam	4.0
Bunches per ring per species	9 trains of 5 bunches	8 trains of 3 bunches	4 trains of 1 or 2	1
Average beam current per species (mA)	340	72	4 at Z peak 4→6 at >90 GeV	0.0008
Beam polarization (%)	—	—	55 at 45 GeV 5 at 61 GeV	e^-: 80
Circumference or length (km)	0.768	0.768	26.66	1.45 +1.47
Interaction regions	1	1	4	1
Magnetic length of dipole (m)	1.6–6.6	1.6–6.6	11.66/pair	2.5
Length of standard cell (m)	16	16	79	5.2
Phase advance per cell (deg)	45–90 (no standard cell)	45–90 (no standard cell)	102/90	108
Dipoles in ring	86	84	3280 + 24 inj. + 64 weak	460+440
Quadrupoles in ring	101 + 4 s.c.	101 + 4 s.c.	520 + 288 + 8 s.c.	—
Peak magnetic field (T)	0.3 / 0.8 at 8 GeV	0.3 / 0.8 at 8 GeV, 2.1 wigglers at 1.9 GeV	0.135	0.597

High-Energy Collider Parameters: e^+e^- Colliders (III)

Table 32.3: Updated in March 2020 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Design parameters for SuperKEKEB may be found in our 2018 edition (Phys. Rev. **D98**, 030001 (2018)) Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

	KEKB (KEK)	PEP-II (SLAC)	SuperKEKB (KEK)
Physics start date	1999	1999	2018
Physics end date	2010	2008	—
Maximum beam energy (GeV)	e^-: 8.33 (8.0 nominal) e^+: 3.64 (3.5 nominal)	e^-: 7–12 (9.0 nominal) e^+: 2.5–4 (3.1 nominal)	e^-: 7 e^+: 4
Delivered integrated luminosity per exp. (fb^{-1})	1040	557	10.57
Luminosity (10^{30} $\text{cm}^{-2}\text{s}^{-1}$)	21083	12069 (design: 3000)	1.88×10^4
Time between collisions (μs)	0.00590 or 0.00786	0.0042	0.0065
Full crossing angle (μ rad)	$\pm$11000*	0	$\pm$41500
Energy spread (units 10^{-3})	0.7	e^-/e^+: 0.61/0.77	e^-/e^+: 0.64/0.81
Bunch length (cm)	0.65	e^-/e^+: 1.1/1.0	e^-/e^+: 0.5/0.6
Beam radius (μm)	H: 124 (e^-), 117 (e^+) V: 1.9	157 4.7	e^-: 16.6 (H), 0.25 (V) e^+: 12.6 (H), 0.25 (V)
Free space at interaction point (m)	+0.75/−0.58 (+300/−500) mrad cone	$\pm$0.2, $\pm$300 mrad cone	$e^-: +1.20/-1.28, e^+: +0.78/-0.73$ (+300/−500) mrad cone
Luminosity lifetime (hr)	continuous	continuous	continuous
Turn-around time (min)	continuous	continuous	continuous
Injection energy (GeV)	e^-/e^+ : 8.0/3.5 (nominal)	e^-/e^+ : 9.0/3.1 (nominal)	e^-/e^+ : 7/4
Transverse emittance (10^{-9} m)	e^-: 24 (57†) (H), 0.61 (V) e^+: 18 (55†) (H), 0.56 (V)	e^-: 48 (H), 1.8 (V) e^+: 24 (H), 1.8 (V)	e^-: 4.7 (H), 0.061 (V) e^+: 2.0 (H), 0.061 (V)
β^*, amplitude function at interaction point (m)	e^-: 1.2 (0.27†) (H), 0.0059 (V) e^+: 1.2 (0.23†) (H), 0.0059 (V)	e^-: 0.50 (H), 0.012 (V) e^+: 0.50 (H), 0.012 (V)	e^-: 0.060 (H), 1×10^{-3} (V) e^+: 0.080 (H), 1×10^{-3} (V)
Beam-beam tune shift per crossing (units 10^{-4})	e^-: 1020 (H), 900 (V) e^+: 1270 (H), 1290 (V)	e^-: 703 (H), 498 (V) e^+: 510 (H), 727 (V)	e^-: 12 (H), 270 (V) e^+: 23 (H), 270 (V)
RF frequency (MHz)	508.887	476	508.887
Particles per bunch (units 10^{10})	e^-/e^+: 4.7/6.4	e^-/e^+: 5.2/8.0	e^-/e^+: 2.76/3.52
Bunches per ring per species	1585	1732	1476
Average beam current per species (mA)	e^-/e^+: 1188/1637	e^-/e^+: 1960/3026	e^-/e^+: 640/819
Beam polarization (%)	—	—	—
Circumference or length (km)	3.016	2.2	3.016
Interaction regions	1	1	1
Magnetic length of dipole (m)	e^-/e^+ : 5.86/0.915	e^-/e^+: 5.4/0.45	e^-/e^+ : 5.9/4.0
Length of standard cell (m)	e^-/e^+ : 75.7/76.1	15.2	e^-/e^+ : 75.7/76.1
Phase advance per cell (deg)	450	e^-/e^+: 60/90	450
Dipoles in ring	e^-/e^+ : 116/112	e^-/e^+: 192/192	e^-/e^+ : 116/112
Quadrupoles in ring	e^-/e^+ : 452/452	e^-/e^+: 290/326	e^-/e^+ : 466/460
Peak magnetic field (T)	e^-/e^+ : 0.25/0.72	e^-/e^+: 0.18/0.75	e^-/e^+ : 0.22/0.19

*KEKB was operated with crab crossing from 2007 to 2010.
†With dynamic beam-beam effect.

High-Energy Collider Parameters: ep, $\bar{\text{p}}$p, pp Colliders

Table 32.4: Updated in March 2020 with numbers received from representatives of the colliders (contact E. Pianori, LBNL). The table shows the parameter values achieved. Parameters for the defunct S$p\bar{p}$S collider may be found in our 2002 edition (Phys. Rev. **D66**, 010001 (2002)). Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; H and V indicate horizontal and vertical directions; s.c. stands for superconducting.

	HERA (DESY)	TEVATRON* (Fermilab)	RHIC Brookhaven	LHC (CERN)		
Physics start date	1992	1987	2001	2009	2015	2026 (HL-LHC)
Physics end date	2007	2011	—	—		
Particles collided	ep	$p\bar{p}$	pp (polarized)	pp		
Maximum beam energy (TeV)	e: 0.030 p: 0.92	0.980	0.255 55% polarization	4.0	6.5	7.0
Max. delivered integrated luminosity per exp. (fb^{-1})	0.8	12	0.38 at 100 GeV 1.3 at 250/255 GeV	23.3 at 4.0 TeV 6.1 at 3.5 TeV	160	250/y
Luminosity (10^{30} $\text{cm}^{-2}\text{s}^{-1}$)	75	431	245 (pk) 160 (avg)	7.7×10^3	2.1×10^4	5.0×10^4 (leveled)
Time between collisions (ns)	96	396	107	49.90	24.95	24.95
Full crossing angle (μ rad)	0	0	0	290	$320 \rightarrow 260^{\dagger}$	500
Energy spread (units 10^{-3})	e: 0.91 p: 0.2	0.14	0.15	0.1445	0.105	0.129
Bunch length (cm)	e: 0.83 p: 8.5	p: 50 $\bar{p}$: 45	60	9.4	8	9
Beam radius (10^{-6} m)	e: 110 (H), 30 (V) p: 111 (H), 30 (V)	p: 28 $\bar{p}$: 16	85	18.8	$8.5^{\ddagger}$	$7^{\ddagger}$
Free space at interaction point (m)	± 2	± 6.5	16	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	10	6 (avg)	7.5	≈ 6	≈ 8	≈ 7.5 (leveled)
Turn-around time (min)	e: 75, p: 135	90	25	180	150	145
Injection energy (TeV)	e: 0.012 p:0.040	0.15	0.023	0.450	0.450	0.450
Transverse emittance (10^{-9} m)	e: 20 (H), 3.5 (V) p: 5 (H), 5 (V)	p: 3 $\bar{p}$: 1	11	0.59	0.3	0.33
β^*, ampl. function at interaction point (m)	e: 0.6 (H), 0.26 (V) p: 2.45 (H), 0.18 (V)	0.28	0.65	0.6	$0.3 \rightarrow 0.29^{\S}$	$0.6 \rightarrow 0.15^{\S}$
Beam-beam tune shift per crossing (units 10^{-4})	e:190 (H), 450 (V) p: 12 (H), 9 (V)	p: 120 $\bar{p}$: 120	73	72	45	86
RF frequency (MHz)	e:499.7 p: 208.2/52.05	53	accel: 9 store: 28	400.8	400.8	400.8
Particles per bunch (units 10^{10})	e:3 p:7	p:26 $\bar{p}$:9	18.5	16	11	22
Bunches per ring per species	e: 189 p: 180	36	111	1380	2556 2544 (i.r. 1/5[¶])	2760 2748 (i.r. 1/5[¶])
Average beam current per species (mA)	e:40 p:90	p:70 $\bar{p}$:24	257	400	510	1100
Circumference (km)	6.336	6.28	3.834	26.659		
Interaction regions	2 colliding beams 1 fixed target (e beam)	2 high $\mathfrak{L}$	6 total, 2 high $\mathfrak{L}$	4 total, 2 high $\mathfrak{L}$		
Magnetic length of dipole (m)	e:9.185; p: 8.82	6.12	9.45	14.3		
Length of standard cell (m)	e:23.5 p:47	59.5	29.7	106.90		
Phase advance per cell (deg)	e:60 p:90	67.8	84	90		
Dipoles in ring	e: 396 p: 416	774	192 per ring + 12 common	1232 main dipoles		
Quadrupoles in ring	e:580 p:280	216	246 per ring	482 2-in-1 24 1-in-1		
Magnet types	e: C-shaped p: s.c., col., warm iron	s.c., $\cos\theta$ warm iron	s.c., $\cos\theta$ cold iron	s.c., 2-in-1 cold iron		
Peak magnetic field (T)	e: 0.274; p: 5	4.4	3.5	8.3[‖]		

*Other TEVATRON parameters: $\bar{p}$ source accum. rate: 25×10^{10} hr^{-1}; max. no. of $\bar{p}$ stored: 3.4×10^{12} (Accumulator), 6.1×10^{12} (Recycler).
†Variable crossing angle decreasing during the fill with the reduction in bunch population
‡Minimum beam radius during levelling
§β^* levelling
¶Number of bunches colliding at the interaction regions (i.r.) 1 (ATLAS) and 5 (CMS).
‖Value for design beam energy of 7 TeV.

High-Energy Collider Parameters: Heavy Ion Colliders

Table 32.5: Updated in March 2020 with numbers received from representatives of the collider (contact E. Pianori, LBNL) The table shows the parameter values achieved. For the LHC, only maximum values for the ATLAS and CMS experiments are provided (ALICE and LHCb have different requirements for energy and luminosity). Design values for a high-luminosity upgrade are also given. Quantities are, where appropriate, r.m.s.; unless noted otherwise, energies refer to beam energy; s.c. stands for superconducting. pk and avg denote peak and average values.

	RHIC (Brookhaven)		LHC (CERN)			
Physics start date	2000	2012 / 2018 / 2018 / 2012 / 2004 2014 / 2002 / 2015 / 2015	2010	2012	2017	$\geq$ 2021 (high lum.)*
Physics end date	—		—			
Particles collided	Au Au	U U / Zr Zr / Ru Ru / Cu Au Cu Cu / h Au d Au / p Au / p Al	Pb Pb	p Pb	Xe Xe	Pb Pb
Max. beam energy (TeV/n)	0.1	0.1	2.51	*p*:6.5 Pb:2.56	2.72	2.76
$\sqrt{s_{NN}}$ (TeV)	0.2	0.2	5.02	8.16	5.44	5.5
Max. delivered int. nucleon-pair lumin. per exp. (pb^{-1})	2639 (at 100 GeV/n)	21 / 36 / 36.9 / 167 / 60 43 / 169 / 124 / 63 (all at 100 GeV/n)	77.8	194	0.05	$\approx 121/y$
Luminosity (10^{27} $cm^{-2}s^{-1}$)	pk: 15.5 avg: 8.7	pk: 0.4 / 4.8 / 3.8 / 12 / 21 170 / 850 / 880 / 7600 avg: 0.6 / 2.2 / 2.1 / 10 / 8 100 / 500 / 450 / 3800	6.1	900	0.4	6.4 (leveled)
Time between collisions (ns)	107	107 / 107 / 107 107/ 107 / 321 107 / 107 / 107 / 107	74.9 / 149.7	99.8 / 149.7	$\approx$ 5500	49.9
Full crossing angle (μ rad)	0	0	320	280	300	340
Energy spread (units 10^{-3})	0.75	0.75	0.11	0.11	0.11	0.11
Bunch length (cm)	30	30	8.0	p / Pb: 9 / 11.5	11	7.9
Beam radius (10^{-6} m)	114†	123† / 87† / 88† / 163† / 145† 136† / 124† / 147† / 128†	21	19	12	17
Free space at inter. point (m)	16	16	38	38	38	38
Initial luminosity decay time, $-L/(dL/dt)$ (hr)	1	-0.35‡ / ∞§ / ∞§ / ∞‡ / 1.8 0.6 / ∞‡ / 0.5 / 0.25	3.3	$\approx$ 2	$\approx$ 6	∞
Turn-around time (min)	30	60¶ / 40¶ / 40¶ / 160¶ / 90¶ 45¶ / 90¶ / 60¶ / 50¶	$\approx$ 180	150	180	$\approx$ 200
Injection energy (TeV/n)	0.011	0.011	0.177	p / Pb: 0.45 / 0.177	0.188	0.177
Transverse emittance (10^{-9} m)	19†	22† /10.7† / 11.2† / 38† / 23† 19† / 22† / 26† / 21†	0.85	0.29	0.3	0.5
β^*, ampl. function at interaction point (m)	0.7	0.7 / 0.7 /0.7 / 0.7 / 0.9 1.0 / 0.7 / 0.8 / 0.8	0.5	0.5	0.4	0.5
Beam-beam tune shift per crosssing (units 10^{-4})	39†	6† / 18† /21† / 14†, 14† / 30† / 42†, 22† 40†, 27† / 53†, 41† / 80†, 59†	15	15	$\approx$ 10	11
RF frequency (MHz)	accel: 28, store: 197		400.8	400.8	400.8	400.8
Particles per bunch (units 10^{10})	0.20	0.03 / 0.1 / 0.1 / 0.4, 0.13 / 0.45 4.5, 0.13 / 13, 0.20 / 22.5, 0.16 / 24, 1.1	0.022 (r.m.s.)	p:2.6 Pb:0.022	0.027	0.018
Bunches per ring per species	111	111 / 111 / 111/ 111 / 37 111 /111 / 111 / 111	733	p:540 Pb:684	16	1232
Average beam current per species (mA)	224	38 / 56 / 61 / 160, 138 / 60 / 125, 143 181, 213 / 313, 176 / 334, 199	23.8	p:16 Pb:15	0.54	32
Circumference (km)	3.834		26.659			
Interaction regions	6 total, 2 high $\mathfrak{L}$		4 total, 3 high $\mathfrak{L}$			
Magnetic length of dipole (m)	9.45		14.3			
Length of standard cell (m)	29.7		106.90			
Phase advance per cell (deg)	93	84 /84 / 84 / 84 / 84 93 / 84(d), 93 / 84(p), 93 / 84(p), 93	90			
Dipoles in ring	192 per ring, + 12 common		1232, main dipoles			
Quadrupoles in ring	246 per ring		482 2-in-1, 24 1-in-1			
Magnet Type	s.c. $\cos\theta$, cold iron		s.c., 2 in 1, cold iron			
Peak magnetic field (T)	3.5		8.3			

*High luminosity upgrade expected >= 2021; will extend throughout HL-LHC running. Very preliminary, conservative estimates.
†Initial value, possibly larger after cooling
‡Negative or infinite decay time is effect of cooling.
§luminosity leveled to flat after set to target value, with cooling
¶measured minimum, not theoretical